Interstate DC Line Performance Assessment Methods

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Abstract--**The Article is focused on interconnection of power systems via High Voltage Direct Current (HVDC) submarine cables, its transmission capacity allocation and utilization. Sufficiency of transmission capability on market formation and operation are investigated as well as role of Power Exchange (PX) and trading principles for HVDC interconnections. Model of Nordic power system and PX data are used for technical/economic calculation and analysis based on market areas price differences and power flows through inter-state connections.**

Index Terms-- **Electricity market, HVDC technology, power flow.**

I. INTRODUCTION

Cooperation between Transmission System Operators (TSOs) of interconnected countries[1] Norway, Sweden, Finland and Denmark is covered by Nordel association. Collaboration within Nordel creates preconditions to better utilize power generation potential deployed in Countries, increase security and stability of power system as well as bring environmental and economic advantages. Recommendations of Association comprise base for technical regulations of power production, grid operation and maintain convenient market environment. Well-functioning power system under Nordel conduced in 1996 to launch first international power exchange Nord Pool for common Nordic power market purposes. Progress in market integration arise in 2000 after transformation on Nordel into organization with state objective to create conditions for an efficient and harmonized Nordic electricity market and ensure process of market development. Furthermore, Nordel provide opportunity for cooperation between TSOs in Nordic and transmission system operators out of Association what makes a contribution to a numbers of physical interconnections between the Nordel region and neighboring countries. Due to harmonization of rules and legislation in different counties associated in Nordel was formulated common code for Nordic grid – The Nordic Grid Code (NGC). The NGC consists of four main Articles: 1) Planning Code, 2) Operational Code (System Operation Agreement), 3) Connection Code 4) Data Exchange Code (Data Exchange Agreement between the Nordic transmission system operators (TSOs) The purpose of the Nordic Grid Code is to achieve coherent and coordinated Nordic operation and planning between the companies responsible for operating the transmission systems, in order to establish the best possible conditions for development of a functioning and effectively integrated Nordic power market. A further objective is to develop a shared basis for satisfactory operational reliability and quality of delivery in the coherent Nordic electric power system [1].

II. NORDIC POWER SYSTEM ANALYSIS

Diversity of power production in the Nordic leads to efforts about reinforcement on internal cross-section connection as well as about common market establishment. Common gain is increasing security and lower costs. In Norway is power generating based mostly on hydro resources. Sweden power production uses predominantly hydro and nuclear power, Finland used a mix of hydro, thermal power and nuclear. Denmark's energy supply was based almost entirely on thermal power with increasing of proportion wind. See Fig.1. Nordic grid operates at the following AC voltage levels: Denmark: 132/150/220/400 kV; Finland: 110/220/400 kV; Norway: 300/420 kV (and 132 kV northern Norway); Sweden: 220/400 kV; The HVDC links between subsystems at 285-400 kV. Cross-border interconnections also constitute numbers of lines on lower voltages.

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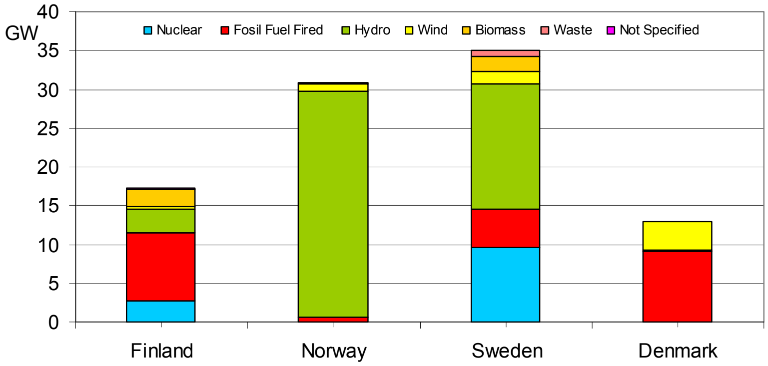

Fig. 1. Installed capacity by energy source of Nordel[1] 2010

Nordic grid comprises power systems of Norway, Sweden, Finland and eastern Denmark (Zealand) with synchronous operation. The western part of Denmark belongs to continental European synchronous area (former UCTE). Furthermore, western Denmark is asynchronously connected to Nordel (Norway and Sweden) via HVDC links. See Fig. 2.

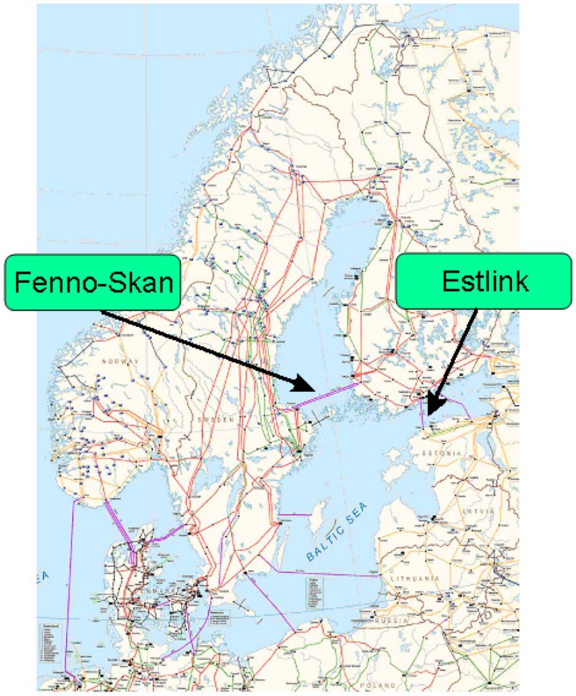

Fig. 2. Nordic power system

Typical feature of Nordel power system is relatively weak coupling between generators due the long distances of transmission lines (high reactance of AC lines) what constraints full utilization of its capacity. Another specific feature of long transmission distances and disperse generators is that capability of interconnections transmit power depends on power flow direction which is related with power production of generators. Especially, considerable proportion of hydro power plants can cause that direction of power flows varies over the year. Further on, after calculations of technical transmission capacity with assuming safety and control margins (typically by 5-10 %) is residual transmission capacity of AC lines put as a disposal for market purposes (commercial capacity). Nominal transmission capacity for DC connections is measured on AC side of rectifier and is determined as a maximum continuous power that can be allowed at the ambient temperature that is not exceeded for more than 4 weeks per year and without affecting the nominal availability [1]. The delivery capacity of the system as a whole is higher than the sum of the individual delivery capacities of the subsystems. As a result of the expansion of transmission capacity between the subsystems, the interconnected Nordic electric power system operates increasingly as a single entity.

New interconnections planning and extension

General common rules summarized in Planning code (article of NGC) determines design of entire Nordic power system so that consumption of electricity should be met at the lowest cost. It means that the power system shall be planned, built and operated so that sufficient transmission capacity will be available for utilizing the generation capacity and meeting the needs of the consumers in a way which is economically best[2]. Planning and construction of new interconnections within Nordel or between Nordel and neighboring systems can affect not only TSOs in direct collaboration but whole Nordic power system with technical and market consequences as well. Therefore, planning of interconnections are coordinated with Nordic grid master plan [2].

III. HVDC INTERCONNECTIONS

Generally, application of DC transmission/interconnection can be mainly due to following reasons:
Requirement to transmit great power at long distance; In cases that for transmission is necessarily used cable (submarine transmission) and problems with considerable charging capacitive currents occurred; Interconnection of unequal power systems or increasing transmission capability of power system by utilization of damping control.
When only technical aspects of transmission has taken a place, comparison 3-phase AC line and bipolar DC line with grounded neutral conductor is summarized in Table 1.[3].

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[1] Nordel collaboration including also Transmission System Operator of Iceland, currently without physical interconnections to rest of Nordel.

[2] For detailed criteria and description of Nordic transmission system planning see [1].

Table 1
COMPARISON OF DC AND AC TRANSMISSION

Matching conditions	**Transmission capability** $\frac{P_{DC}}{P_{AC}}$	**Power losses** $\frac{\Delta P_{DC}}{\Delta P_{AC}}$	**Voltage decrease** $\frac{\Delta U_{DC}}{\Delta U_{AC}}$ $\xi = 80°$ $\cos\varphi = 0{,}95$
Equal U_{crit} of corona and cross-section of wires	1,405	$\frac{3}{8}\cos^2\varphi$	0,528
Equal U_{crit} of corona and weight of wires	2,455	$\frac{1}{6}\cos^2\varphi$	0,317
Equal level of insulation and cross-section of wires	1,65	$\frac{1}{3{,}7}\cos^2\varphi$	0,451

Total losses of direct transmission are higher due the losses in converter stations.

A. HVDC submarine cable Fenno-Skan

Submarine HVDC cable commissioned in 1989 which reinforced coupling of power systems of Finland and Sweden. Cable length is 200km. Currently owned by Fingrid (Finland) and Svenska Kraftnät (Sweden). Link is used for power exchange in both directions. Rated voltage 400 kV, presently operates as monopolar (planed bipolar extension). Transmission capacity is temperature-dependent, normally at 550 MW with short overload possibility at the 600 MW.

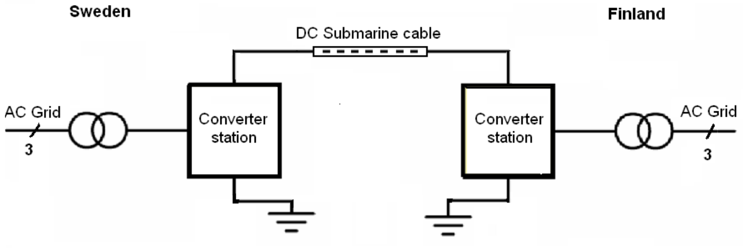

Fig. 3. Principal Fenno-Skan configuration

Main assets of interconnection are reduction of transmission distances between south-western Finland and east central Sweden, which represents areas with high concentration of consumption and generating power. Interconnection also provides possibility for power flow redistribution between 400 kV AC lines on north and Fenno-Skan (middle). Such operation brings total system losses reduction by up to 40 MW. Furthermore, Fenno-Skan has also been provided with damping control regulators and emergency power control features, which stabilize the power systems in such a way that the power transfer capability between northern and central Sweden can be increased by 250 MW and in same amount also increased capability of 400 kV northern AC lines between Sweden and Finland.

Operation and capacity redistribution

Monitoring, operation and control concerning 400 kV AC links and Fenno-Skan in Sweden is carried out by Grid Supervisor at Network Control of SvK in Racksta and in Finland from Operation Centre of Fingrid in Helsinki. Fenno-Skan regulation responsibility alternates between Finnish and Swedish side every half of calendar year. Transmission capacity of all interconnections is calculated on daily basis by Operation centres in Racksta and Helsinki. Available trading capacity is obtained as total transmission capacity minus determined margin for regulation purposes. As a starting point for trading capacity distribution between northern AC lines and Fenno-Skan is used basic distribution with rules in compliance with Nordic grid operation code. Elbas (Intraday trading of Nord Pool power exchange) and supportive power trading across the border are not handled in basic distribution. During periods when a disturbance in power system occurred loss minimization is not employed. Parties involved in cooperation do not pay any compensation for loss minimization benefit, only non-notified balance power is financially settled [1]. In period 2008-2012 is planned extension of Fenno-Skan with second pole (Fenno-Skan 2) due the increases in generation capacities, above all, integration of wind park near Gävle and uprates in nuclear power plant Forsmark 3. Changes are also concerned reinforcement 400 kV AC northern lines and modifications of substations [4].

B. HVDC submarine cable Estlink

Efforts about increasing of HVDC interconnection capacities between Nordel and rest of continental Europe are primarily based on market interests as well as better utilization of hydroelectric power generation deployed in Nordel and predominant thermal power generation in Continent. These interests are strongly powered also by European Commission with idea to establish common EU energy market. Estlink, submarine HVDC cable linked up subsystems of Finland (Espoo substation - AC 400 kV) and Estonia (Harku substation - AC 330 kV). Link with total length 210 (2 times 105) km was commissioned in 2006. Operational voltage level of bipolar construction is +/- 150 kV.

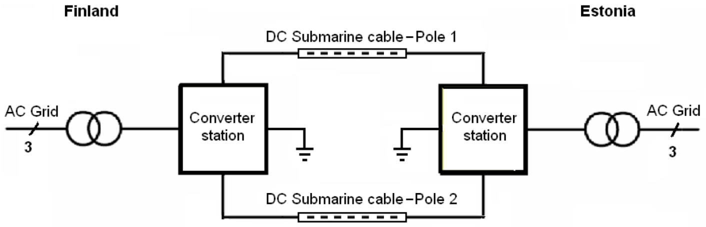

Fig. 4. Principal Estlink configuration

Maximal transmission capacity at the 350 MW with possibility to transmit energy in either direction is primary meant for market purposes (commercial operation). Besides, interconnection improved security of supply in Baltic that creates potential channel for purchasing electricity from Nordic. Construction of cable not induced any grid improvement on Finnish side. Estimated annual import 2,5 TWh from Estonia represent approximately 3% of total current Finnish consumption.

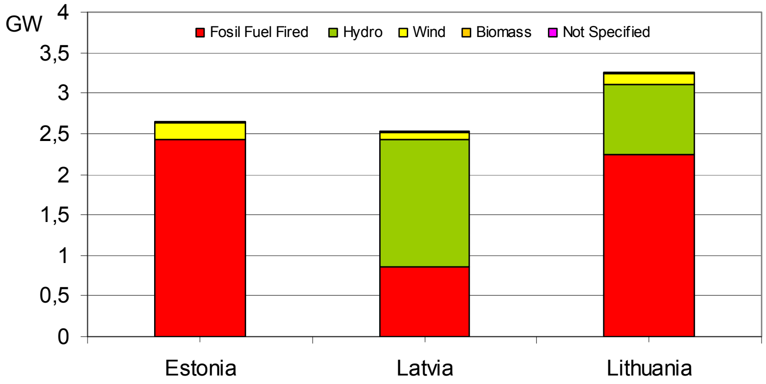

Fig. 5. Installed capacity by energy source in Baltic 2010

To evaluate new possible interconnections was launched multiregional study between Nodel, Baltso and PSE operator (Polish TSO) related to technical-economic impacts of new links [5].

IV. NORD POOL SPOT

Presently, Nord Pool Spot runs largest international electricity market on the World. Providing services for day-ahead market (Elspot) and intra-day market (Elbas) spot trading with physical electricity. As a result of matching supply and demand bids at the spot market, final spot price and trading volumes are determined. Due to potential limitations in transmission capacity spot market in Nordic was divided into Nord Pool spot bidding areas.

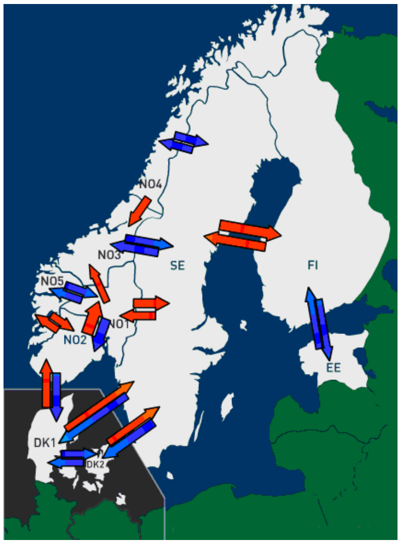

Fig. 6. Nord Pool Spot Areas

Except Denmark and Norway which are subdivided into several spot price areas, boundaries are identical with national borders.

TSOs allocate available transmission capacity on a base of production and consumption forecast. Subsequently, available capacity is allocated at Nord Pool spot market for trading purposes. Allocation of available transmission capacity is done before Nord Pool spot pricing. The available capacities for transmission are reported to Nord Pool pre bidding and are taken into account when price calculation is performed. When no congestion appeared, the prices in different areas are the same (Area price = System price). Market splitting is used if there is congestion. Solving tasks with structural congestion is related to grid investments in case that it is socio-economically feasible, otherwise market splitting is utilized, i.e. dividing the market into separate price areas. Adequate transmission capacity with effective utilization is therefore one of the basic requirements to achieve well functioning and effective electricity market.

Price differences between areas after utilization of transmission capacity between them generate an ownerless income on the spot market, trading flow from the area with a lower price to the area with a higher price. In situations when flow goes from high price area to low price area (towards low price area) due to specific operations or dispatch optimization by TSOs, generating of ownerless costs occurred [4].

These ownerless costs and incomes are referred as congestion rent. Within the Nordic region this income is allocated to the TSOs as owners of the transmission grid. Calculation of congestion rent as follows:

$$(P_B - P_A)F_{A\mapsto B} = C_R \qquad (1)$$

P_A - Area price in area A, [m.u./MWh];

P_B - Area price in area B, [m.u./MWh];

$F_{A\mapsto B}$ - Planned Elspot flow in specific hour from area A to area B, [MW];

C_R - Aggregated congestion rent [m.u.].

Sharing of congestion rent between TSOs is based on Sharing Agreement which provide two possible sharing options. First, calculates adequate share (participation) of all TSOs on Five prioritized projects within Nordel related to Nordic grid development. Second divide congestion rent in two equal shares only between affected TSOs[3] [1]. Incomes of TSOs are commonly used for reduction of tariffs or investments to transmission grid. New Estlink bidding area at Nord Pool Spot was launched on 1 April 2010 and connects Estonia to Nordic electricity market. The long term goal is to create a Baltic market connected to the Nordic market through Nord Pool Spot [5]. The Estlink cable is operated by company AS Nordic Energy Link (NEL). NEL was founded by Baltic and Finnish companies. These share NEL Company (transmission capacity on Estlink) as follows: Baltic companies Eesti Energia (39.9%), Latvenergo (25%) and Lietuvos Energija (25%) and Finnish companies Pohjolan Voima and Helsingin Energia (Finestlink) remaining 10.1%. Shareholders will sell before 2013 entire NEL company to TSOs Fingrid (Finland) and Elering (Estonia) [7].

Suitable environment for Estonian market establishment by Nord Pool Spot arised after Latvenergo and Eesti Energia offered their shares of Estlink capacity to the Estonian and Finnish transmission system operators Elering and Fingrid. This step ensured sufficient capacity for opening the Estlink bidding area.

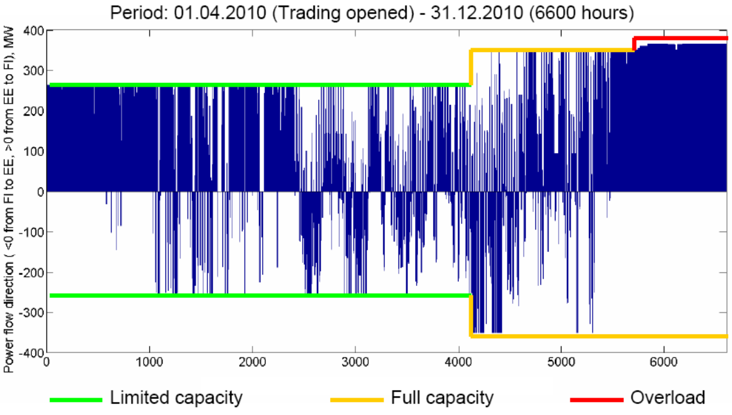

Fig. 7. Estlink power flow utilization by Elspot, 2010

Available transmission capacity allocated for the Elspot-market was 252 MW from Finland to Estonia and 262 MW from Estonia to Finland. Since September 2010 TSOs of Finland and Estonia rented full cable capacity from owners and offered for market purposes. After new agreement the available transmission capacity is 350 MW in both directions.

Increasing of transmission capacity through Estlink is very positive for the market development in the Baltic and Nordic. Adequacy capacity is one an important step in markets integration and further on, towards common European market with electricity.

V. LOSSES OPTIMIZATION MANAGEMENT

A. *Fenno-Skan loss minimization and benefits sharing*

Loss minimization in Finnish and Swedish grids by Fenno-Skan aggregates benefits which are divided equally between TSOs. Benefits calculation as well as distribution between parties (Fingrid & SvK) is based on following principles [1]: The overall benefit to the system in particular hour is defined as the positive difference between the calculated overall loss overheads during basic distribution and during the real reference value. As reference value minimal point is usually used. See Fig. 8.

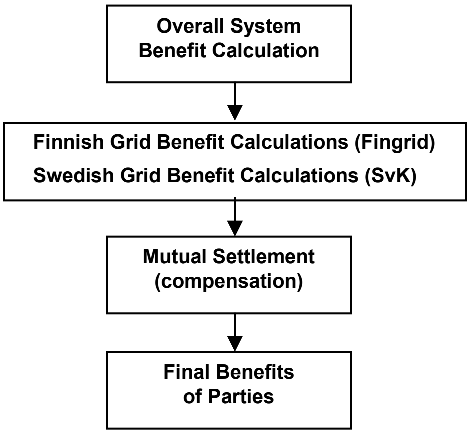

Fig. 8. Fenno-Skan benefit evaluation and distribution

B. *Estlink losses calculation*

Estlink power flow analysis estimates markets activity and price differences of interconnected areas. Calculations are based on physical power flow through Estlink at hourly basis from 1 April 2010 until 31 December 2010. In Fig. 9 is shown example of price differences between Estonia and Finland which caused a physical power flow through Estlink. In assumed period only flow from Estonia to Finland appeared.

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[3] For detailed description of sharing principles and changes in sharing options check: http://www.nordpoolspot.com

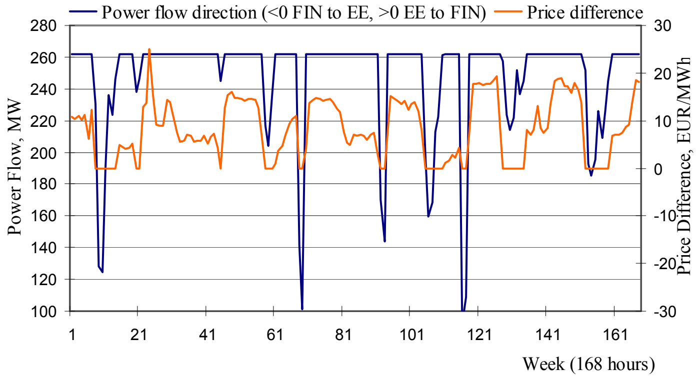

Fig. 9. Price difference & Estlink power flow

Transmitted volume in assumed period represents 1,524249 TWh of which from FI to EE is 0,243934 TWh and EE to FI is 1,280315 TWh. Calculation of Estlink losses were performed by Estlink Losses Formula. Total calculated losses caused by power flow in both directions are 75,348 GWh of which from FI to EE is 12,814 GWh and EE to FI is 62,534 GWh.

After variable transmission costs of cable were calculated, in compliance with price differences between Areas on hourly basis, costs of *ignored* transmission losses was obtained.

Figure 10 shows one week period Estlink power flow and caused (calculated) power losses.

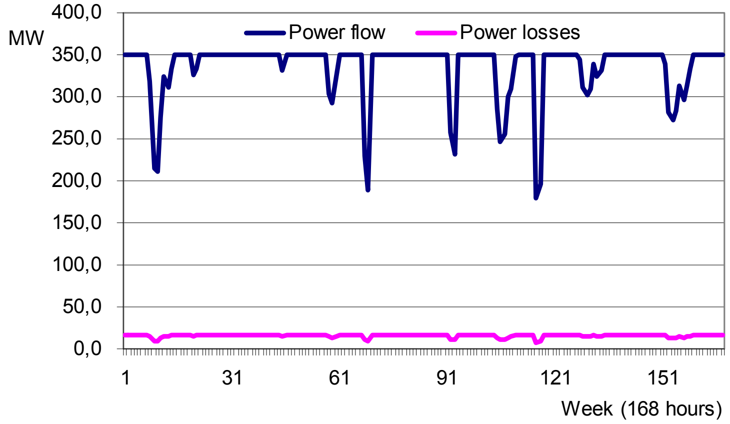

Fig. 10. Physical Estlink power flow & calculated losses

VI. MODEL OF POWER SYSTEM FOR LOSSES ESTIMATION

For the analysis of Fenno-Scan in the Nordic countries the modified Nordic32-bus test system is used. Its close resemblance to a real power system in Sweden where more generation units are in the north and heavy load centres in the south. The model consists of 33 buses, 28 synchronous generators, 51 branches, 3 DC lines and a total of 25 loads. As a starting point the simplified single diagram of the CIGRE Nordic32-bus test system [8].

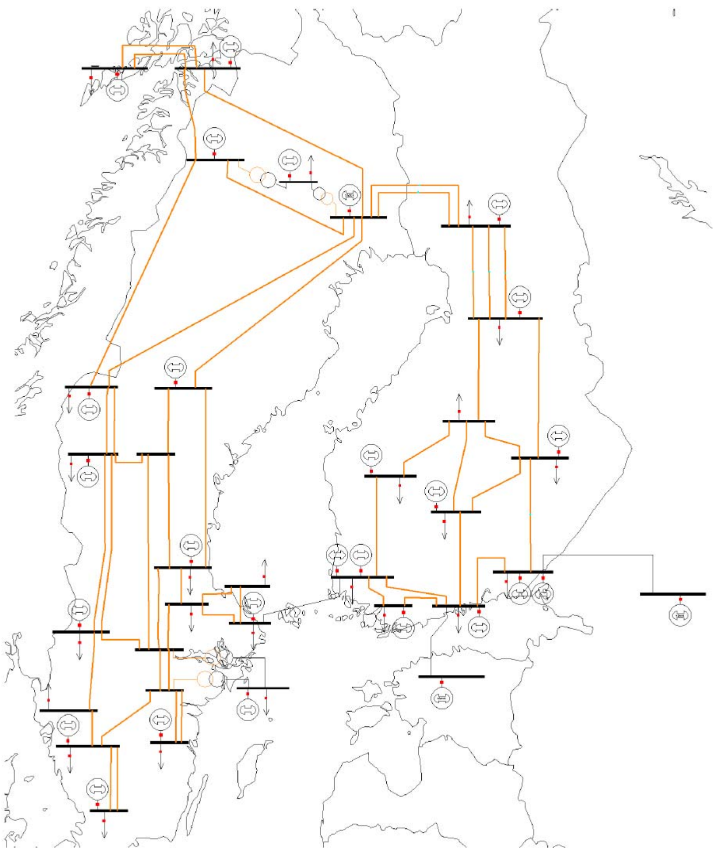

Fig. 11. Model of Nordic grid

Model of Nordic grid was created in Power World Simulator which is designed to simulate high voltage power system operation. Software contains power flow analysis and losses calculation. Simulation and parameters of grid elements takes into account current state of real power system in Nordic.

VII. CONCLUSIONS

In this paper described Interstate DC Line Performance Assessment Methods in Liberalized Market conditions. This method will be used for power flow analysis and losses calculation to estimates markets activity and price differences of interconnected areas.

It will provide facility for market participants properly organize their long-term and short-term power balance including investments into new infrastructure, in that way helping to organize power balance in the whole system and to reducing financial losses.

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IX. BIOGRAPHIES

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Irina Oleinikova was born in Riga, Latvia, on September 16, 1974. She received the BSc, E.E., MSc and Dr.sc.ing. degrees from the Riga Technical University, in 1994, 1995, 1997 and 2000 respectively. She is senior researcher in the Laboratory of Power Systems Mathematical Modelling at the Institute of Physical Energetics. Her main research interests include Methods for Mathematical Modelling of Electrical Networks and Systems; Methods for Development of Power systems Planning; Dynamic Optimization Methods and Decision Systems. She is author more then 90 papers, including 4 books.